GEOMORPHIC ASSESSMENT OF ACTIVE TECTONICS IN THE ACAMBAY GRABEN, MEXICAN VOLCANIC BELT

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ABSTRACT

Spatial variations of Quaternary deformation and tectonic activity of faults along the Acambay graben are assessed using geomorphic and morphometric approaches. The Acambay graben is an east–west trending structure of apparent Quaternary age, located in the central part of the Mexican Volcanic Belt, which gives rise to pronounced scarps over a distance of about 80 km. Continuing tectonic activity in the Acambay graben is confirmed by recent well documented seismic episodes.

The intensity of active tectonics has been interpreted through a detailed geomorphic study of the fault-generated mountain fronts and fluvial systems. The combined geomorphic and morphometric data provide evidence for relative variations in tectonic activity among the Acambay graben faults. Geomorphic indices suggest a relatively high degree of tectonic activity along the Venta de Bravo and the Acambay–Tixmadeje faults, followed, in order of decreasing activity, by the Pastores, Temascalcingo and Tepuxtepec faults. Spatial variations within faults have also been identified, suggesting a higher level of tectonic activity at the tips of the faults. This pattern of variation in the relative degree of tectonic activity is consistent with field evidence and seismic data for the Acambay graben. Geomorphic evaluation of the Acambay graben faults suggests that the Acambay–Tixmadeje and Venta de Bravo faults, and specifically the tips of these faults and a central segment near the town of Venta de Bravo, should be considered as areas of potentially high earthquake risk. © 1998 John Wiley & Sons, Ltd.

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INTRODUCTION

Geomorphic indices are useful tools in the evaluation of active tectonics because they can provide rapid insight concerning specific areas within a region which is undergoing adjustment to relatively rapid, and even slow, rates of active tectonics (Keller, 1986). The Acambay graben provides an opportunity to study systematically landforms produced or modified by active tectonic processes and to deduce spatial variations of Quaternary deformation and active tectonics in the region. This article reports the results of a geomorphic study applying morphometric and geomorphic field evidence to earthquake hazard assessment of the Acambay graben. This part of the Mexican Volcanic Belt exhibits great internal variation in the relief and continuity of mountain fronts. Some workers have already documented Quaternary tectonics, active surface faulting and historical seismicity in this part of central Mexico (Urbina and Camacho, 1913; Suter *et al*., 1991, 1992, 1995; Astiz, 1980). However, none of these studies has used a systematic analysis of landforms to define patterns of the relative rates of tectonic activity and earthquake hazard in the region.

The scope of this paper includes a brief outline of the tectonic, seismic, geological and geomorphic setting, a discussion of the geomorphic indices that are useful in defining relative rates of uplift, and discussion of the relative rates of Quaternary mountain front uplift in the study area. Uplift and/or erosion, and to a lesser extent volcanic activity during the Quaternary, account for most of the configuration of the landscape elements observed. Only major, localized tectonic processes are considered. Exclusively those mountain fronts which

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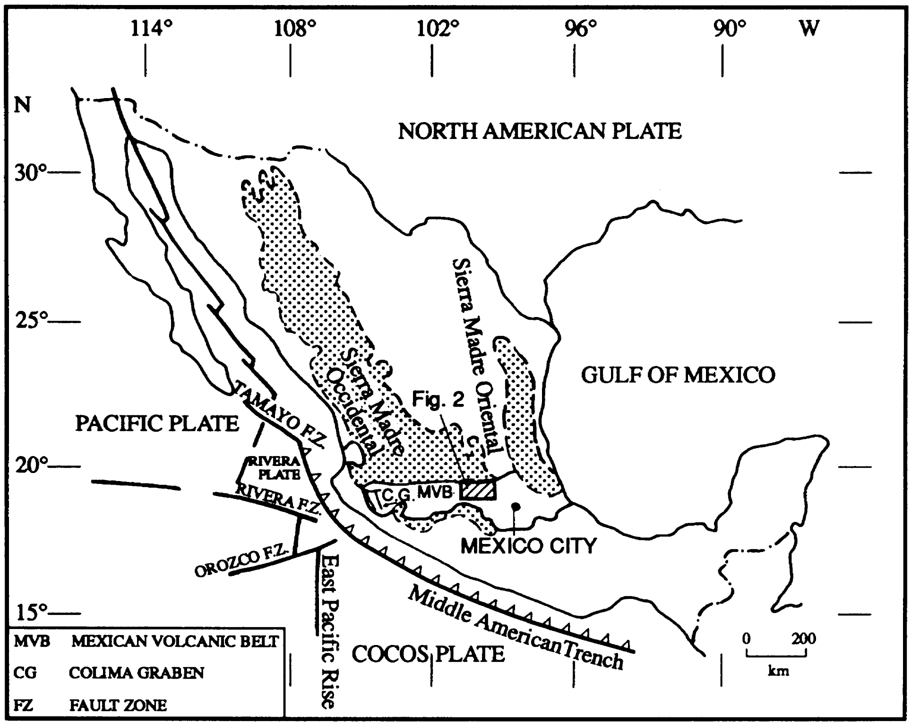

Figure 1. Tectonic setting of the Mexican Volcanic Belt. The obliquely shaded area shows the location of the Acambay graben

are more than 10 km long are analysed. A mountain front is considered as being an escarpment and part of the basin adjacent to the escarpment.

The Acambay graben is located in the central part of the Mexican Volcanic Belt between latitude 19° 45′–20° 00′ north and longitude 99° 45′–100° 25′ west (Figure 1). It is an east–west trending structure of apparent Quaternary age which gives rise to pronounced scarps over a distance of about 80 km. Continuing tectonic activity in the Acambay graben is confirmed by recent well documented seismic episodes such as the Acambay event of 1912 (Urbina and Camacho, 1913) and the Venta de Bravo event of 1979 (Astiz, 1980), both of which caused significant vertical displacement along faults flanking the graben.

The aim of this research is to assess the spatial variations of Quaternary deformation and tectonic activity of the faults along the Acambay graben. This is accomplished using geomorphic and morphometric approaches in the study of the fault-generated mountain fronts and fluvial systems. The analysis endeavours to interpret the relative intensity of active tectonics through the study of landforms. The results of this analysis can be applied for earthquake hazard reduction.

Tectonic setting

The Mexican Volcanic Belt is a 20–150 km broad structure extending for around 1000 km, in an approximately east–west direction, from the Pacific Ocean to the Gulf of Mexico (Figure 1). It is an active, mostly calc-alkaline volcanic chain (Verma, 1987), which is genetically associated with subduction of the Cocos plate along the Middle American Trench.

The central part of the Mexican Volcanic Belt is characterized by generally east–west striking faults which form a series of *en echelon* graben along its length. This structural style, which is indicative of an extensional regime, is clearly related to the volcanism and regional-scale tectonics of the area. It has been proposed that the Acambay graben, along with the other series of *en echelon* graben and horsts of the Mexican Volcanic Belt, is the product of episodically active left-lateral shear in the upper brittle section of the crust generated in the Middle American trench and the newly developing Colima graben (Mooser and Ramírez-Herrera, 1989; Luhr *et*

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al., 1984). Plate convergence, which seems to have been the dominant tectonic factor in southern Mexico since the Late Jurassic, appears to have resulted in the activation of a transtensive, left-lateral fault system along the Mexican Volcanic Belt (Urrutia-Fucugauchi and Böhnel, 1988).

Several other workers have proposed normal faulting with a left-lateral strike-slip component as the main neotectonic process in the central part of the Mexican Volcanic Belt (Astiz, 1980; Johnson, 1987; Johnson and Harrison, 1990; Mooser, 1969; Mooser and Ramírez-Herrera, 1989; Soler, 1990; Suter, 1991; Suter *et al*., 1991).

Seismicity

Earthquakes have been recorded on several of the faults in the region during historic time (Suter *et al*., 1992). The $M_s = 6{\cdot}9$ Acambay event of 19 November 1912, located near the town of Acambay, generated vertical displacements of up to 0·5 m (Urbina and Camacho, 1913), while the most recent significant seismic activity occurred in 1979. The main shock (the $M_b = 5{\cdot}3$ Venta de Bravo event) occurred on 22 February. The focus of the main shock was located $27{\cdot}8 \pm 4{\cdot}2$ km east of Maravatío at a depth of $8{\cdot}2 \pm 2{\cdot}9$ km with the epicentre being close to the outcrop of the Venta de Bravo fault. The focal mechanism of the shock, which shows a major left-lateral strike-slip component, has an east–west oriented fault plane with a dip of 60°N (Astiz, 1980).

GEOMORPHOLOGICAL AND GEOLOGICAL SETTINGS

The study area includes faulted mountain fronts formed by the uplifted northern and southern blocks of the graben. The central part of the graben is occupied by large inner depressions, filled with tuff and lake deposits, separated by series of cinder and lava cones and by Mt Temascalcingo. The faulted mountain fronts typically reach elevations in excess of 200 m above the surrounding terrain with some blocks exceeding 500 m. The Río Lerma provides the major drainage across the graben, and smaller streams drain perpendicular to the mountain fronts. Climate here is temperate rainy to subhumid.

The geology of the Acambay region has been described by Fries *et al*. (1977), Sánchez-Rubio (1984) and Silva-Mora, (1979). Mountain fronts along the Acambay graben are formed mainly by bedrock of volcanic, volcaniclastic, igneous and locally metamorphic units of Miocene to Quaternary age. Some of them exhibit a narrow piedmont composed of colluvial and alluvial deposits.

The general arrangement of the faults that constitute the Acambay graben shows dominant east–west trend which typically defines the fronts of the graben, and a secondary NNW–SSE fault trend which is oblique to the east–west trending faults of the Acambay graben (Figure 2). The Acambay graben exhibits a major fault discontinuity, which is apparently concordant with the regional NNW–SSE systems of faults, and this highlights the asymmetrical structure of a half-graben in the western part of the graben. East–west trending faults typically define the fronts of subparallel mountain ranges.

Active faults in the Acambay graben are grouped into five major east–west trending systems: the Acambay–Tixmadeje system, the Tepuxtepec faults, the Pastores fault, the Venta de Bravo system and the Temascalcingo faults, as illustrated in Figure 2. These faults typically define the fronts of the mountain ranges that border the graben to the north and south. The geomorphological evidence indicative of neotectonic activity shows that the Acambay graben faults consist of normal north-facing and normal south-facing faults, most having experienced minor left-lateral displacement (Suter *et al*., 1992; Ramírez-Herrera, 1994; Ramírez-Herrera *et al*., 1994).

The Acambay graben mountain fronts are broken close to the central part of the graben by the flat alluvial plain of the Río Lerma which breaks the northern and southern ranges. The eastern part of the Acambay graben is almost symmetrical. The northern flank is formed by a prominent east–west trending master fault together with a parallel fault at the base of a sharp mountain front, reaching elevations up to 500 m above the surrounding terrain. The southern flank, by contrast, is formed by an east–west trending master fault, forming a mountain front which typically reaches elevations of less than 250 m above the surrounding terrain. Both fronts – Acambay–Tixmadeje to the north and Pastores to the south – show a discontinuous piedmont, up to 0·5 and 0·75 km wide respectively. No major rivers drain perpendicular to these fronts, with the exception of the Río Lerma crossing the Pastores front.

A pair of NNW–SSE regional lineaments divides the Acambay graben into a western and an eastern part. The western part of the graben appears to have a half-graben structure: it is asymmetric, with one prominent,

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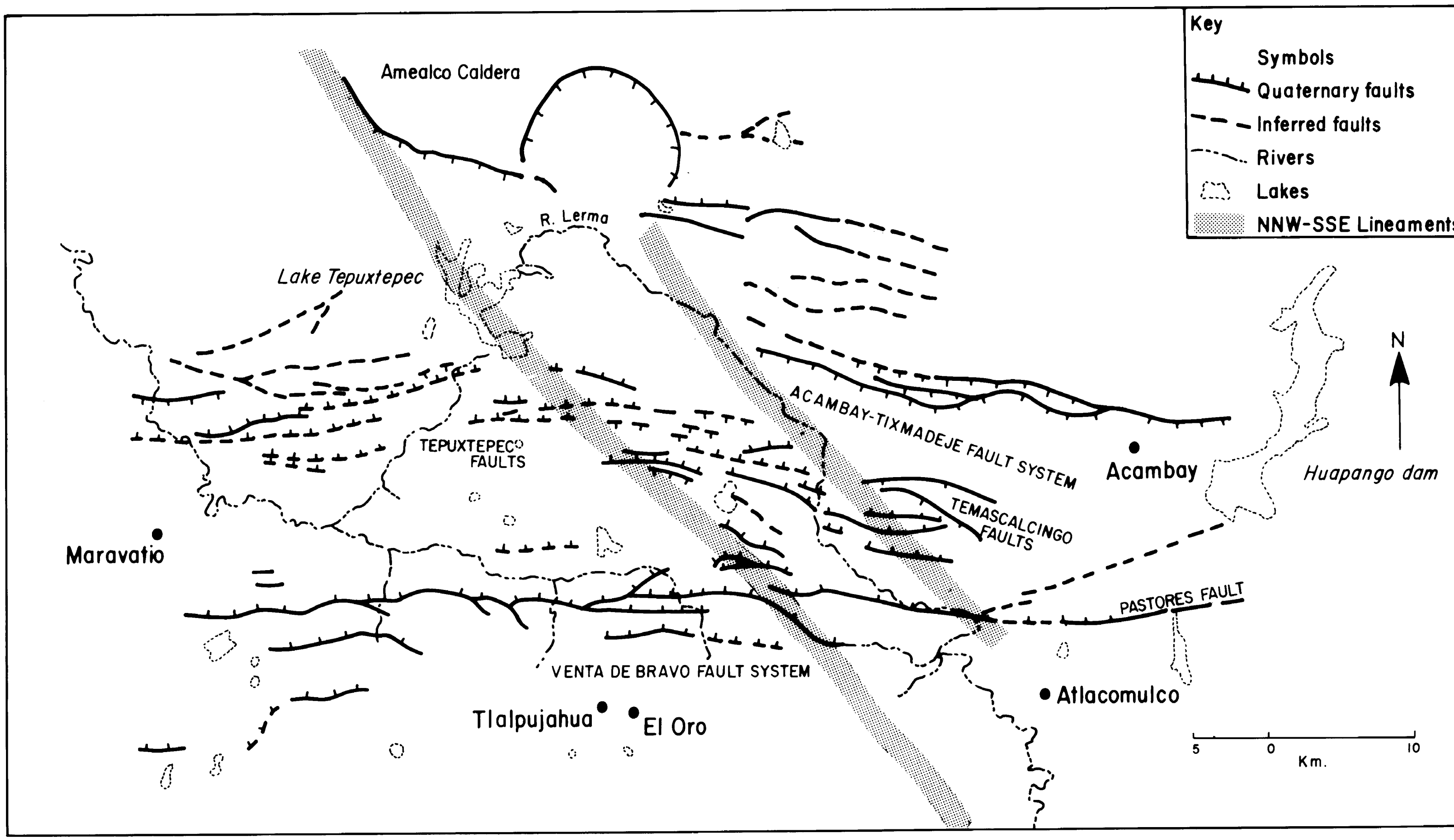

Figure 2. Overview map of late Cenozoic faults in the Acambay graben, central part of the Mexican Volcanic Belt

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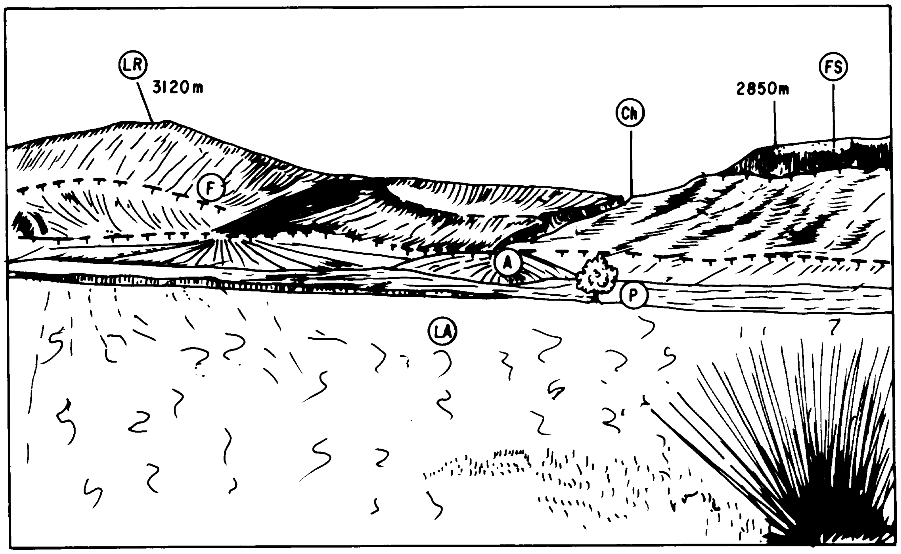

Figure 3. Morphological sketch of the Acambay–Tixmadeje mountain front, northern flank of the Acambay graben (for location see Figure 2). Symbols: A, alluvial fan; FS, fault scarp; P, piedmont; LA, lacustrine-alluvial basin; LR, linear ridges; F, fault; Ch, channel

east–west trending, master fault at the base of the Venta de Bravo mountain front. The front reaches elevations of 200 to 500 m above the surrounding terrain. Several major streams drain perpendicular to the front. The structural geology here is characterized by a main master fault facing to the north and several parallel *en echelon* faults located to the south of the front (Figure 2). At the base of the front a continuous piedmont extends up to 3 km wide. In contrast, on the northern side of the graben, only truncated minor east–west trending normal faults, north- and south-facing, define the front. The mountain front here is discontinuous, reaching elevations up to 150 m above the surrounding terrain, with several minor streams draining perpendicular to the front and a discontinuous piedmont which is 0·5 to 1·5km wide.

Mt Temascalcingo is a composite volcano, located in the central part of the graben. The structural geology here is characterized by east–west trending parallel faults facing to the north and south, which break the central part of the volcano and form a look-alike graben structure (Figure 2). Fault scarps here reach elevations up to 250 m above the surrounding terrain. Only minor streams drain perpendicular to the fault scarps. The central part located between these faults forms a depression filled with alternating lacustrine and volcanic deposits.

Geomorphic evidence of tectonic activity

Field reconnaissance of the Acambay graben fault scarps has revealed much geomorphic evidence of active tectonics (Ramírez-Herrera, 1994). The Acambay–Tixmadeje fault scarp exposes striations and slickensides at the footwall, at the western termination of the faulted mountain front. In addition, numerous well defined triangular facets mark the sharp mountain front providing evidence of Quaternary uplift of the front.

Fault-displaced lava cones and unentrenched alluvial fans also suggest active faulting (Figure 3). Alluvial fans at the base of the footwall of the mountain front are still receiving sediments at the fanhead and this indicates active tectonics in this area (Bull and McFadden, 1977).

The Pastores front, particularly in its western part, shows steep fault scarps, an almost undissected and continuous escarpment, and river offsets. The Río Lerma, which crosses the fault from south to north, exhibits two river terraces that rise and continue downstream, where the river flows on the downthrown block. The origin of these terraces might be the response to changes in river base level due to uplift of the southern block. Elevated lake deposits, tilted to the north, are exposed at the base of the fault suggesting active faulting in this area. In addition, some scarps and fractures produced in an adjacent depression, filled with lake deposits, were reported during the 1912 earthquake. Small terraces of probable tectonic origin were also observed on the alluvial plain.

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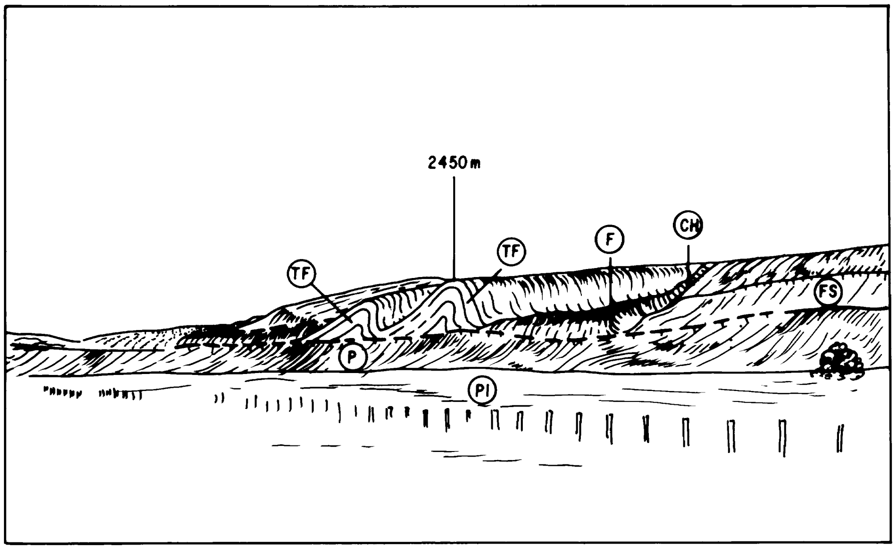

Figure 4. Morphological sketch along the Venta de Bravo fault showing triangular facets and V-shaped valleys. Symbols: Fs, faults scarp; P, piedmont; F, fault; TF, triangular facets; Pl, alluvial plain; Ch, channel

The western termination of the Pastores fault provides micro- and mesomorphological evidence of active faulting. Here, it is possible that some of the displacement of the Pastores fault is being transferred to the Venta de Bravo fault (Suter *et al*., 1992).

The easternmost area of the Pastores front shows scarce geomorphic evidence of tectonic uplift, but reveals variations in escarpment morphology: the fault exhibits triangular facets developed at the base of the scarp. Most of the streams show V-shaped valleys, and the escarpments exhibit active incision that may be a response to active faulting. Lava flows and scoria cones seem to be vertically displaced; however, in some areas the fault seems to be partially buried by Quaternary lava flows.

The fault-bonding mountain front of the Venta de Bravo fault is an almost straight line extending for 46 km. Despite the general straightness of the front there are several breaks along the master fault indicating the boundaries between different geomorphologically defined segments (Figure 2). The morphology of the escarpment suggests fault control and field evidence confirms active faulting in the area. Well developed triangular facets and V-shaped valleys demonstrate active incision presumably being produced by active uplift. Stream offsets and a fault plane observed in the knickpoint of the El Cuervo River expose subvertical striations (La Huerta) indicative of a lateral component displacing the active fault. Other exposed fault scarps exhibiting micromorphological evidence of active tectonics where found along the Venta de Bravo mountain front.

Field data provide several lines of evidence of active faulting towards the central part of the front. The escarpment immediately south of the town of Venta de Bravo is steep and exhibits triangular facets divided by V-shaped valleys indicating valley downcutting (Figure 4). Excellent exposures at the base of the scarp show a striated fault plane. The striations here are subvertical and indicate a minor left-lateral horizontal component (Suter *et al*., 1992). A compression ridge rises at the zone of intersection of two faults. This ridge is the product of the lateral displacement of these faults producing compression stress at this point and consequent uplift. The area between the faults consists of a depression filled with alluvial deposits, indicating extension. The southern fault exhibits sag ponds at the base of the scarp. Combined, these elements suggest a pull-apart structure. Rock slides were observed, suggesting recent active tectonics.

Fault scarps along the eastern part of the Venta de Bravo mountain front are steep in the upper part and exhibit an incipient piedmont at their base. The morphology of this area shows linear ridges with asymmetrical slopes. Some triangular facets are developed to the west of this area. Several sag ponds are located along the base of the fault scarp.

The eastern termination of the Venta de Bravo mountain front shows steep fault scarps, triangular facets, V-shaped valleys, elongated ridges, and sag ponds filled with alluvial material at the base of the fault scarps,

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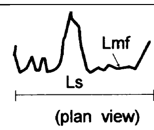
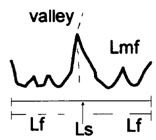
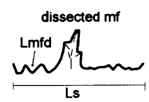
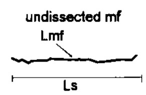
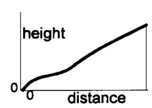
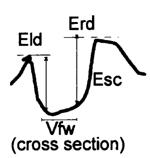
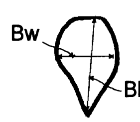
Table I. Summary of the morphometric parameters used in tectonic landform analysis of individual mountain fronts of the Acambay graben (after Wells *et al*., 1988)

Morphometric parameter	Mathematical derivation*	Measurement Procedure	Purpose	Significance	Source
S_{mf} - Mountain front sinuosity	$S_{mf}=L_{mf}/L_s$		Reflect a balance between the tendency of stream and slope processes to produce irregular (sinuous) mountain front and vertical active tectonics that tend to produce a prominent straight front (Keller, 1986)	$S_{mf}=1{\cdot}0$ – most tectonic activity $S_{mf}>1{\cdot}0$ – less tectonic activity	Bull and McFadden, 1977
Percentage faceting along mountain fronts	L_f/L_s		Define the proportion of a mountain front that has well defined triangular facets, using the ratio of the cumulative lengths of facets to overall mountain front length	Tectonically active fronts display prominent, large facets that are generated and/or maintained by recurrent faulting along the base of the escarpments, i.e. high percentage faceting	Wells *et al*., 1988
F_d, Percentage dissected mountain fronts	L_{mfd}/L_s		Define the proportion of a mountain front that has been dissected into distinct facets	Most tectonically active mountain fronts tend to be less dissected, i.e. low F_d values	Wells *et al*., 1988
E_u, Percentage undissected escarpments	L_{ce}/L_s		Define the proportion of a mountain front that has not been dissected	Most tectonically active mountain fronts show laterally continuous undissected escarpments, i.e. high E_u values	This study
Stream long-profiles			Define any irregularities in channel slope that reflect disequilibrium conditions	Disequilibrium conditions suggest tectonic disruption of the bed	Hack, 1973
V_f, Valley floor – valley height ratio	$V_f=2V_{fw}/[(E_{ld}-E_{sc})+(E_{rd}-E_{sc})]$		Define the ratio of the width of the valley floor to the mean height of two adjacent divides	The index reflects differences between broad-floored canyons with relatively high values of V_f, and V-shaped canyons with relatively low V_f values	Bull and McFadden, 1977
B_s, Drainage basin shape ratio	$B_s=B_l/B_w$		Define the planimetric shape of a basin	High B_s values = elongated basins, i.e. high tectonic activity; low B_s values = circular basins, i.e. low tectonic activity	This study, after Cannon (1976)

* symbols: L_{mf}—length of mountain front along the mountain-piedmont junction, L_s—straight-line length of the front, L_f—cumulative lengths of facets, L_{mfd}—the length of dissected mountain front, L_{ce}—cumulative length of all laterally continuous undissected escarpments, V_{fw}—width of valley floor, E_{ld} and E_{rd}—respective elevations of the left and right valley divides and E_{sc}—elevation of the valley floor, B_l—length of the basin, measured from its mouth to the most distant drainage divide, B_w—width of the basin measured across the short axis.

suggesting active tectonics at the termination of the Venta de Bravo fault.

Geomorphic tectonic features displayed at the Temascalcingo fault scarps include fault channel control, triangular facets, and high escarpments located at the base of the northern escarpments. In addition, fault planes are exposed on the northern flank of Mt Temascalcingo which exhibit vertical and horizontal displacement.

Although geomorphic features in the field provide evidence of active tectonics along the Acambay faulted mountain fronts, a morphometric approach is also applied to the faulted mountain fronts in order to quantify relative rates of tectonic activity. The tectonic activity has impacted the fluvial systems and rates of dissection, and thus forms the base for applying morphometric techniques that are used in studying the uplifted mountain fronts. Morphometric data provide evidence of relative rates of uplift which complement and enable comparison with the field data. This information is of great value in order to identify and reduce earthquake hazard in the region.

METHODS

Most of the morphometric variables used in this study were developed by Hack (1973), Orlova (1975), Bull and McFadden (1977), Rantsman (1979) and Wells *et al*. (1988) (Table I).

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The theoretical basis for the morphometric analysis involves relative adjustments between local base-level processes (tectonic uplift, stream downcutting, basin sedimentation and erosion) and the fluvial systems which cross structurally controlled topographic mountain fronts (Bull and McFadden, 1977). This type of morphometric analysis has not previously been applied to the fault-controlled mountain fronts of the Acambay graben.

Five major study areas, comprising mountain fronts associated with the systems of faults constituting the graben, were selected for morphometric analysis (Figure 2). Mountain fronts were selected for this study on the basis of topographic, lithological, geomorphological and structural continuity. Owing to the large size of the area of study (2400 km^2) it was necessary to apply sampling for some of the morphometric indices used in this study. Sample selection was determined according to particular geomorphological criteria that provided high reliability and confidence in the representativeness of the morphometric data produced.

Tectonic geomorphic indices: criteria for selection

1. Mountain fronts. In this study mountain fronts were defined as major fault-bounded escarpments with measurable relief exceeding two contour intervals (20 m). For the analysis, long escarpments were subdivided along-strike into discrete segments with similar geological and morphological characteristics. The following criteria were applied: (a) intersection with cross-cutting drainage large in scale relative to the front, (b) abrupt changes in lithology, (c) abrupt changes in the major morphological characteristics of the mountain front relative to adjoining front segments, and (d) changes in mountain front orientation (Wells *et al*., 1988).

(i) Mountain front sinuosity. Because the plan view of most faults is straight or only gently curved, the degree of erosional modification of tectonic structures can be measured by a mountain front sinuosity index (Bull and McFadden, 1977). This is defined as:

$$S_{\mathrm{mf}} = L_{\mathrm{mf}}/L_{\mathrm{s}}$$

where L_{mf} is the length of mountain front along the mountain–piedmont junction and L_{s} is the straight-line length of the front. The S_{mf} index reflects a balance between the tendency of stream and slope processes to produce an irregular (sinuous) mountain front and vertical active tectonics to produce a prominent straight front (Keller, 1986). Values of S_{mf} approach 1·0 on the most tectonically active fronts, whereas S_{mf} increases if the rate of uplift is reduced or ceases, and erosional processes begin to form a sinuous front which becomes more irregular with time (Table I). However, values of S_{mf} depend on image scale, and small topographic maps produce only a rough estimate of mountain front sinuosity. Therefore, mountain front sinuosity and all morphometric variables were measured on large-scale topographic maps (1:50 000, with 10 m contour intervals).

(ii) Facets. A facet is a triangular to polyhedral shaped hillslope situated between two adjacent drainage structures within a given mountain front escarpment. Tectonically active fronts display prominent, large facets which are generated and/or maintained by recurrent faulting along the base of the escarpments (Bull, 1978, 1984). Less tectonically active mountain fronts contain fewer, smaller and/or more internally dissected facets. Nevertheless, both small and large facets occur in tectonically active areas (Wells *et al*., 1988). More tectonically active mountain fronts tend to be less dissected, giving a range from laterally continuous undissected escarpments to a nearly continuous front with only a few large and distinct facets with minimal internal dissection (Wells *et al*., 1988).

Three indices related to facet development were used in this study: (a) the proportion of faceting along mountain fronts, (b) the proportion of dissected mountain fronts, and (c) the proportion of undissected escarpments (Table I).

The proportion of undissected escarpments was developed in this study as a complement to the proportion of dissected mountain fronts. Mountain fronts that showed laterally continuous undissected escarpments were distinguished from individual facets in order to avoid confusion in the systematic definition of facets.

2. Fluvial systems. The morphology of small- to medium-sized channels and valleys (5–20 km long, and exceptionally the more than 50 km long Río Lerma) that cross mountain fronts may reflect the impact of local base-level changes due to relative uplift along active structures associated with the frontal escarpments (Wells *et al*., 1988). This study uses detailed longitudinal profiles, cross-river sections, cross-valley relief ratios, and

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basin shape ratios measured in 10 m contour maps to isolate anomalous patterns in channel or valley forms attributable to tectonic activity.

(i) Longitudinal profiles. The semi-log plot of an equilibrium long profile is a straight line on the axes if the river is flowing across uniform bedrock (Hack, 1973). Overstepped reaches that cannot be explained by resistant lithology in the stream bed reflect disequilibrium conditions, and a common cause of such disequilibrium is tectonic disruption of the bed (Bishop and Bousquet, 1989). The utility of this parameter is based in the fact that irregularities in channel slope might reflect disequilibrium conditions, suggesting uplift along active faults. Upwardly concave profiles may suggest prolonged basin and channel degradation associated with longer periods of time since basement lowering. More upwardly convex profiles suggest less channel downcutting, continued base-level lowering and/or less time since base-level fall (Table I) (Wells *et al*., 1988).

Longitudinal stream profiles were plotted at 10 times vertical exaggeration in order to highlight any irregularities in channel slope. A small number of streams cross transversally the fault-bounding mountain fronts in the Acambay graben. Long profiles were plotted for those streams that reach the drainage divide and transversely cross the main fault systems along the graben. The bedrock on the channel bed was also considered for the long profile analysis.

(ii) River cross-sections and cross-valley relief ratios. Transverse valley profiles were defined using a valley floor–valley height ratio variable. Comparison of the width of the floor of a valley with its mean height provides an index that indicates whether the stream is actively downcutting (being dominated by the influence of a base-level fall at some point downstream) or is primarily eroding laterally into the adjacent hillslopes. This index can be expressed by:

$$V_f = 2V_{fw}/[(E_{ld} - E_{sc}) + (E_{rd} - E_{sc})]$$

where V_{fw} is the width of valley floor, E_{ld} and E_{rd} are the respective elevations of the left and right valley divides and E_{sc} is the elevation of the valley floor (Bull and McFadden, 1977). The index reflects differences between broad-floored canyons with relatively high values of V_f, and V-shaped canyons with relatively low values (Table I).

The location of the cross-valley transects within a drainage basin affects the values of cross-valley relief ratios (V_f). Thus, in this study transverse valley profiles were located 0·5 km upstream from the mountain front in smaller drainage basins, and in large drainage basins transverse valley profiles were located 0·5 and 1 km upstream from the mountain front. The reason for working with different ranges for the location of the cross-valley transects is that valley floors tend to become progressively narrower upstream from the mountain front in larger drainage basins for a given mountain range. Values of V_f may also vary widely among streams with different drainage basin areas, discharges and underlying bedrock lithologies. Consequently V_f ratios were not used directly in this study to estimate the relative levels of tectonic activity of specific fronts, as this would require comparison of V_f values among streams of variable size and lithology. Instead, several V_f values were determined along the length of streams in each subarea with similar geological and morphological characteristics (Bull, 1978; Wells *et al*., 1988). The data were combined with the longitudinal profile and valley morphology to indicate changes in valley and profile morphologies suggesting localized uplift in channel reaches upstream from mountain fronts crossed by a given stream.

(iii) Drainage basin shape. The typical basin of a tectonically active mountain range is elongate, and basin shapes become progressively more circular with time after cessation of mountain uplift (Bull and McFadden, 1977). Thus, the planimetric shape of a basin may be described by an elongation ratio of the diameter of a circle with the same area as the basin to the distance between the two most distant points in the basin (Cannon, 1976). Here the planimetric shape of a basin is described by an elongation ratio B_s that can be expressed as:

$$B_s = B_l/B_w$$

where B_l is the length of the basin, measured from its mouth to the most distant drainage divide, and B_w is the width of the basin measured across the short axis (Table I). The index reflects differences between elongated basins with high values of B_s and more circular basins with low values. Drainage basin widths are much narrower near the mountain front in tectonically active areas where the energy of the stream has been directed

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primarily to downcutting; by contrast, a lack of continuing rapid uplift permits widening of the basins upstream from the mountain front.

The drainage basin shape was calculated for the 27 drainage basins of streams that cross the main faults of the Acambay graben. The purpose of calculating the drainage basin shape (B_s) index was to identify elongated basins which reveal primarily downcutting in areas of continuing rapid uplift.

Morphometric parameters used in tectonic landform analyses of individual mountain fronts are related and in some cases interdependent. Mountain fronts with decreasing amounts of tectonic uplift relative to basal erosion or pedimentation, which are characterized by increasingly large values of mountain front sinuosity (S_{mf}), will also show an increase in dissection (F_d) produced by large drainage basins into distinct facets. However, not all dissection will produce facets and an active front will also display facets that are generated or maintained by recurrent faulting along the base of the escarpments (Bull, 1984). The more tectonically active mountain fronts tend to be less dissected, ranging from laterally continuous, undissected escarpments to a nearly continuous front with only a few large and distinct facets (Wells, 1988).

Morphometric indices used for fluvial systems are equally well correlated; streams with more upwardly convex longitudinal profiles will generally show V-shaped cross-river sections, which are apparently dominated by downcutting in response to local base-level fall. These streams also generally show elongate drainage basins (high B_s values) and narrow valley floors (low V_f values in actively uplifting areas (Bull and McFadden, 1977).

The results of morphometric indices are influenced by factors such as lithology, climate and vegetation of the study area. Mountain fronts of the Acambay graben are formed in bedrock, mostly volcanic rocks, in a semi-arid region. Therefore, homogeneity in the form–process development should be expected and any alteration in these values should be attributed to tectonic activity.

Most of the morphometric indices used in this study have already been successfully applied in studies of the tectonic geomorphology of active extensional and compressional terranes in arid or semi-arid regions of the southwestern United States (Bull and McFadden, 1977; Bull, 1984) and in a semi-tropical region of Costa Rica (Wells *et al*., 1988). Thus, the applicability of these indices to the study area, with some landscape similarities to the study regions mentioned above, can here be tested. However, the degree of importance of each index varies in this study and it can be graded. Special attention is paid to values of faceting and continuous undissected escarpments, which might more clearly reflect variations in the degree of uplift along-strike and within each front. Because streams in the study area are scarce or relatively small, morphometric indices on fluvial systems are of less relevance than other morphometric indices measured on the fronts.

RESULTS

Variations in the morphology of the fault-defined mountain fronts that form the Acambay graben provided the basis for the morphometric assessment of relative degrees of tectonic activity. To simplify the analysis and discussion of morphometric indices in the Acambay graben, five areas are considered: (1) Acambay–Tixmadeje, (2) Tepuxtepec, (3) Pastores, (4) Venta de Bravo and (5) Temascalcingo. Subsequently, faulted mountain fronts forming these areas were subdivided along-strike into smaller units called subareas on the basis of the geologic and geomorphologic criteria mentioned above (Figure 5) (Wells *et al*., 1988).

Within the study region differences occur in the morphologic and morphometric expression of internal mountain fronts, and within fronts, associated with the active tectonic environment of the Acambay graben. Low sinuosity (1·1) on the Acambay–Tixmadeje fronts reflects a relatively straight fault-bounded mountain front. A high proportion of continuous undissected escarpments (26·5 per cent), low values of dissection (12·5 per cent) and elongated drainage basins, characteristically occur in the westernmost part of the front (subarea 1) (Table II), suggesting a relatively higher degree of tectonic uplift in this area. However, a relatively high proportion of faceting (29 per cent), semi-elongate basins and the proximity to the location of the 1912 earthquake support relatively high uplift also in subarea 3 of the front (Table II and Figure 6).

The application of morphometric indices to the Tepuxtepec front has presented some problems as this area does not represent a continuous mountain front. Morphometric indices measured on fault escarpments revealed some continuous undissected escarpments (25·8 per cent) (Table II). However, the proportion of continuous

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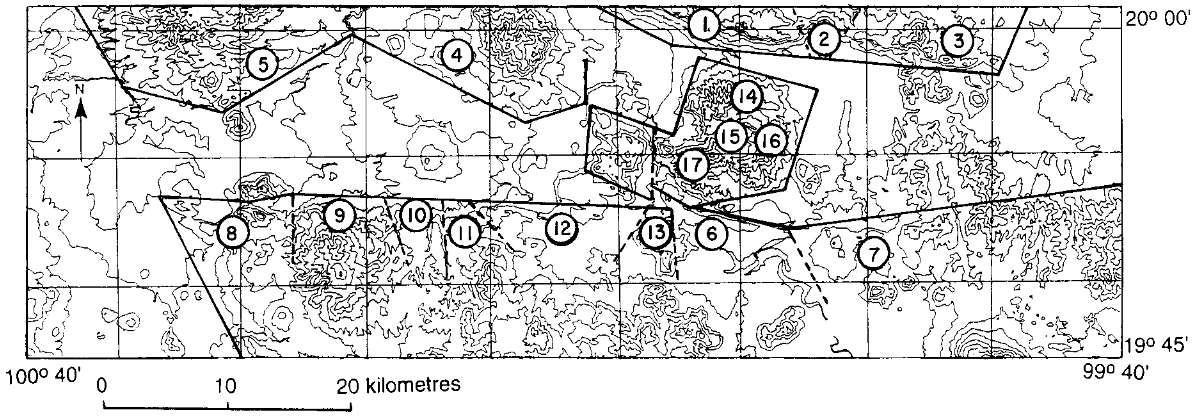

Figure 5. Generalized topographic map of Acambay graben including the study areas and subareas for morphometric analysis. Thick lines indicate the approximate boundaries of the areas studied (numbers and dashed lines indicate subareas): Acambay-Tixmadeje (1–3), Tepuxtepec (4,5), Pastores (6,7), Venta de Bravo (8–13) and Temascalcingo (14–17). Source maps for this digital compilation are from the Instituto Nacional de Estadística, Geografía e Informática (Scale 1:50000)

Table II. Values of the morphometric indices for the mountain fronts of the Acambay graben

Mountain front and subareas	S_{mf}	L_f/L_s	E_u	F_d	V_f	B_s
Acambay–Tixmadeje	1·10					
1		15	26·5	12·5	1·30	6
2		3	5·9	33	0·52	1·1
3		29	8·8	37·5	0·09	1·8
Tepuxtepec	1·32					
4		–	28·6	–	–	–
5		–	23	–	0·3	–
Pastores	1·20					
6		–	78·6	–	0·6	1·5
7		17	0	22	0·8	2·3
Venta de Bravo	1·06					
8		0	80	1·2	0·3	0·9
9		31	0	16·2	0·7	2·1
10		28	16·7	4·6	0·2	2·3
11		40	0	4·2	0·8	2·9
12		0·7	77	1·2	2·5	6
13		–	50	1·2	0·4	1·6
Temascalcingo	n/a					
14		6	48·8	23	1	1·6
15		3	40	25	0·5	3·2
16		31	50	33	0·5	1·1
17		33	0	33	–	–

See Table I for explanation of symbols, n/a—not applicable

undissected escarpments is still the lowest in the study region and no facets have developed on this front, suggesting a low degree of uplift in this area (Figure 6). The application of morphometric indices to the only large stream in the area proved unsuccessful as these values (Table II) are not representative of the tectonic processes experienced on the complete front.

Morphometric indices applied to the Pastores fault-bounded mountain front show a high proportion of continuous undissected escarpments (78·6 per cent), relatively low dissection, convex river long-profiles and V-shaped valleys (Table II) within the western part (subarea 6), indicating a higher degree of tectonic activity in this part (Figure 6).

The Venta de Bravo mountain front is the straightest front in the study area (S=1·06). The combined morphometric data, including facet proportion, escarpment dissection, V_f ratios, longitudinal stream profiles, cross-river sections and basin shape indices, provide additional evidence for relative variations in tectonic

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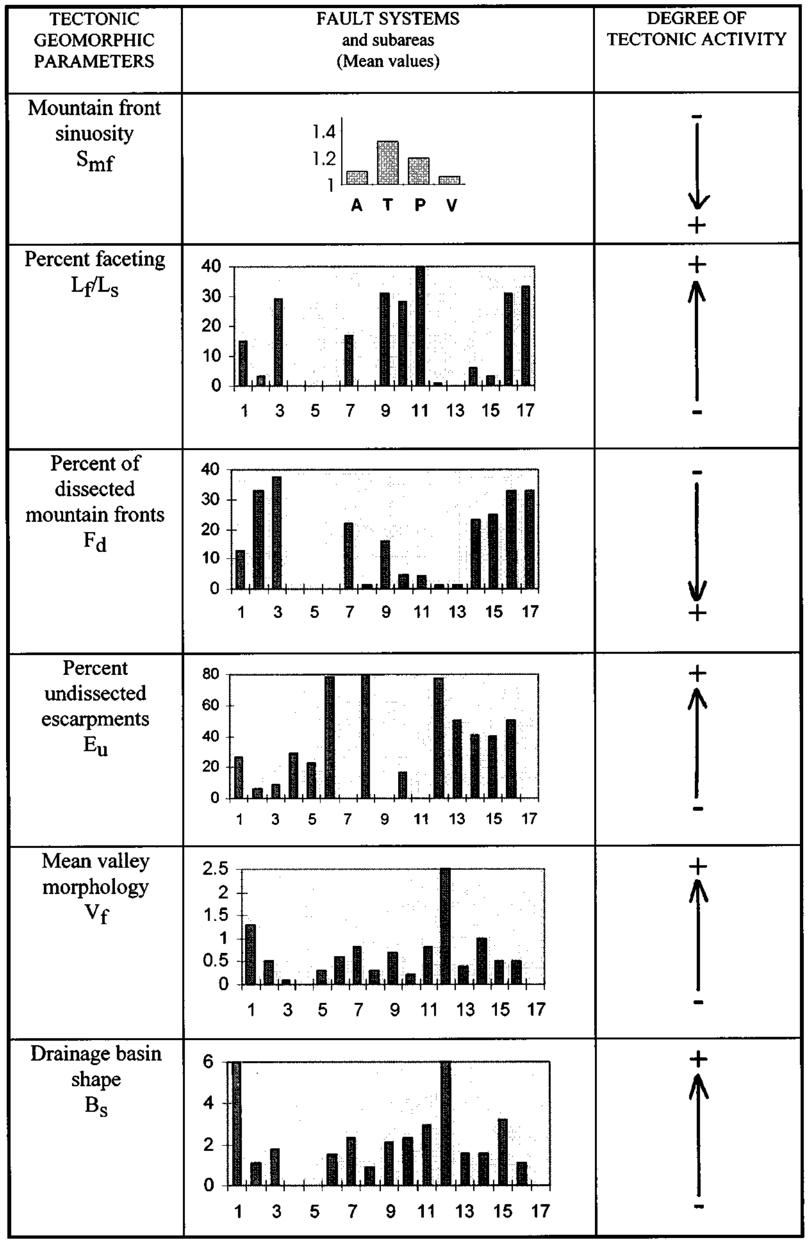

Figure 6. Tectonic geomorphic parameters and relative degrees of tectonic activity. Variations in tectonic geomorphic parameters of mountain fronts with different fault control along the Acambay graben. Letters indicate study areas and numbers indicate subareas: A (1–3), Acambay–Tixmadeje fault; T (4,5), Tepuxtepec faults; P (6,7), Pastores fault; V (8–13), Venta de Bravo fault; 14–17, Temascalcingo faults.

activity among subareas of the Venta de Bravo front (Table II). For example, the high proportion of continuous undissected escarpments, high proportion of faceting, and low proportion of dissected escarpments, together with low V_f values and river-long profiles indicate that the terminal parts of the mountain front (subareas 8, 12–13) and subarea 11 (in the central part) (Table II) display relatively higher degrees of uplift (Figure 6). The highest values of faceting, E_u and B_s, for the whole Acambay graben are found in the Venta de Bravo mountain front (Table II), identifying this front as the one with the highest degree of tectonic activity in the entire region (Figure 6).

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Finally, morphometric indices (the L_f/L_s ratio, E_u, F_d, V_f and B_s) applied on the Temascalcingo fault scarps do not seem to suggest a significant difference between subareas (Table II). The relatively high values of dissected escarpments, in conjunction with the development of facets and some continuous escarpments, indicate moderate levels of tectonic activity (Figure 6). Generally, morphometric indices here suggest a lower degree of tectonic activity than in the Venta de Bravo, Acambay–Tixmadeje and Pastores fronts (Figure 6).

Examination of all morphometric data suggests the following points regarding the mountain fronts and subareas of the Acambay graben.

(1) The Venta de Bravo and Acambay–Tixmadeje fronts show the highest level of uplift in the Acambay graben. These fronts display primarily mountain front characteristics indicative of relatively high degrees of tectonic activity in the study region. The stream valley characteristics provide supporting evidence for high tectonic activity (Figure 6).

(2) In contrast, mountain fronts in the Pastores, Temascalcingo and Tepuxtepec fronts are more sinuous, with lower development of facets, increased dissection and semi-elongate stream basins, suggesting relatively lower rates of tectonic uplift on these fronts than on those mentioned above. An exception to this pattern is the westernmost part of the Pastores faulted mountain front where the front displays an almost continuous escarpment with low dissection, elongated basins with V-shaped valleys, suggesting relatively higher rates of uplift in this sector of the front (Figure 6).

(3) The combined morphometric data suggest a general pattern of localized higher uplift on the terminations of the Venta de Bravo and Acambay–Tixmadeje fronts. An exception to this pattern is a sector (subarea 11), located in the central part of the Venta de Bravo front, where a high degree of uplift has been deduced from morphometric indices (Figure 6).

Morphometric analysis indicates spatial variations of tectonic activity along the Acambay faulted mountain fronts, pointing to a general trend of increasing tectonic activity towards the terminations of the Venta de Bravo and Acambay–Tixmadeje mountain fronts.

DISCUSSION AND CONCLUSIONS

The morphometric approach, applied to the faulted mountain fronts and fluvial systems of the Acambay graben in central Mexico, has a significant value in providing information on the spatial variability of relative rates of tectonic uplift and, if combined with field and seismic data, provides a basis for earthquake hazard assessment.

Combining morphometric results with data produced during several visits to the field, it was found that the trend of spatial variations in relative levels of tectonic activity obtained from morphometric indices is supported by geomorphic field evidence and seismic data for the faulted mountain fronts.

Field reconnaissance of the Venta de Bravo and Acambay–Tixmadeje faulted mountain fronts showed a series of geomorphic evidence of tectonic activity such as well defined triangular facets, unentrenched alluvial fans, steep fault scarps, V-shaped valleys, elongated ridges and sag ponds, together with micromorphological evidence of tectonic activity (e.g. fault plane striations). These geomorphic features are particularly abundant on the terminations of these fronts, and in the central part of the Venta de Bravo front. Well defined triangular facets divided by V-shaped valleys, steep fault scarps and a series of exposed fault planes with striations support morphometric results indicative of the highest levels of tectonic activity in these areas of the Acambay graben.

Elevated lake deposits, a series of river terraces and the presence of exposed fault striations along the steep fault scarp on the western part of the Pastores front confirm a higher degree of tectonic activity which was detected via morphometric analysis. Similarly, the absence of triangular facets and obliterated fault scarps on the Tehuantepec front coincides with lower levels of tectonic activity detected via the morphometric approach.

Therefore, it is concluded that the morphometric expression of mountain fronts associated with active tectonic environments showed marked differences within the five study areas. The combined morphometric and field data provided evidence for relative variations in tectonic activity among the identified areas and subareas of the Acambay graben. Low-sinuosity, fault-controlled morphology of the scarps, high values of the proportion of faceting and undissected escarpments are representative of the Venta de Bravo mountain front, suggesting a relatively high degree of tectonic activity (Figure 7).

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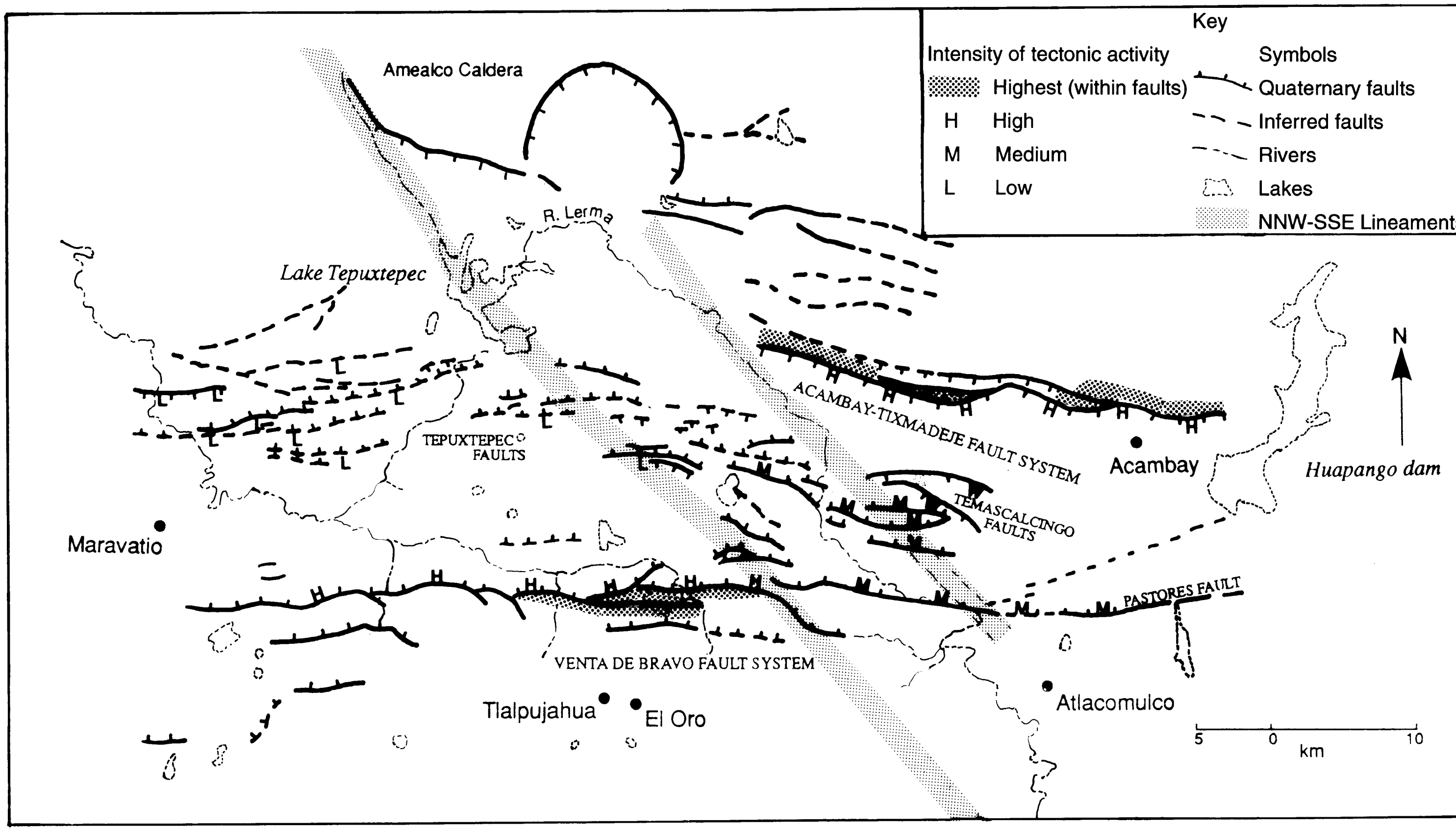

Figure 7. Spatial variations in levels of tectonic activity along the Acambay graben

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The combined morphometric and field data suggest that the Acambay–Tixmadeje mountain front exhibits the second highest tectonic activity in the Acambay graben, followed by the Pastores, Temascalcingo and Tepuxtepec fronts. However, it should be recognized that the Temascalcingo area does not, strictly speaking, represent a mountain front. Nevertheless the morphology and morphometry of the fault escarpments constituting this area were evaluated in this analysis (Figure 7).

Variations within fronts were also identified (Figure 7). This morphometric pattern of variation in the degree of tectonic activity is consistent with field evidence and seismic data for the Acambay graben. The Venta de Bravo and Acambay–Tixmadeje faulted mountain fronts have experienced historic seismic events ($M_b = 5{\cdot}3$ and $M_s = 6{\cdot}9$ respectively).

The combined morphometric, geomorphic and seismic data proved to be a valuable tool in determining the spatial variations in relative levels of tectonic activity and in providing data for the assessment of areas that possess a major earthquake risk in the region of study. This study emphasizes the need for chronological data of the Acambay graben faults in order to determine rates of tectonic activity and temporal variations in seismic activity.

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